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BARE CRITICAL ASSEMBLIES OF ORALLOY AT INTERMEDIATE CONCENTRATIONS OF U-235

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CRITICALITY HAZARDS

ABSTRACT

Bare cylindrical critical assemblies were constructed of stacked plates of fully enriched oralloy and tuballoy. Proportions were adjusted to give average U-235 concentrations of 53.6%, 37.7%, and 29.0%. Approximate relations between critical parameters and U-235 concentration (c) are:

critical mass (total U, corrected to sphere) $= \text{const. } c^{-1.71}$,

Rossi alpha $= \text{const. } c^{0.92}$,

$$\int_0^\infty nv\sigma_f(25)\,dE \Big/ \int_0^\infty nv\sigma_f(28)\,dE = \text{const. } c^{-0.60}$$

$$\int_0^\infty nv\sigma_f(37)\,dE \Big/ \int_0^\infty nv\sigma_f(28)\,dE = \text{const. } c^{-0.29}$$

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INTRODUCTION

The critical assemblies described in this report were studied at Pajarito to satisfy a request for properties of systems of bare oralloy at intermediate U-235 concentrations. The experimental program extended from March to May of 1952, with some checks in April and May 1953 and in January 1954.

The basic material for the assemblies was 15 plates of Oy (93.4), 10-1/2" OD x 7/8" ID x 8 mm thick, each weighing about 8.36 kg, and 30 plates of Tu, 10-1/2" OD x 7/8" ID x 6 mm thick, each weighing 6.36 kg. Oy and Tu plates were stacked in different proportions to give cylindrical assemblies with various average concentrations of U-235. Equal numbers of Tu and Oy plates (pairs) gave an average U-235 concentration of 53-1/2%, two Tu plates with each Oy (triplets) averaged Oy (37-1/2%), and three Tu plates per Oy (quadruplets) averaged Oy (29%).

1. Assembly System

Each stack was set up on the Comet remotely-controlled assembly machine, which consists essentially of an hydraulic lift beneath an A-frame. The lower two-thirds of each assembly was supported on the hydraulic lift by means of Al spacers, and the upper portion was slung from a pneumatic cylinder on the A-frame. The two portions were brought together by remote control, and automatically "scrammed" apart in case of excessive fission rate or power failure.

Figure 1, a diagram of one of the assemblies (known locally as Jemima), shows the arrangements for supporting the two portions, and the way in which Oy and Tu fillers for the 7/8" diam. axial hole were staggered in order to lock the stack together. Also indicated is the vernier reactivity control, a 4" x 8" x 1/2" thick plate of Tu of which the position (along a parallel to the assembly axis) is controlled by means of an air cylinder. For reactivity adjustments of intermediate magnitude, one of the 10-1/2" Tu disks was segmented into 8 "pies," so that the assembly could be topped with an appropriate fraction of a plate. Figure 2 is a photograph of a typical assembly.

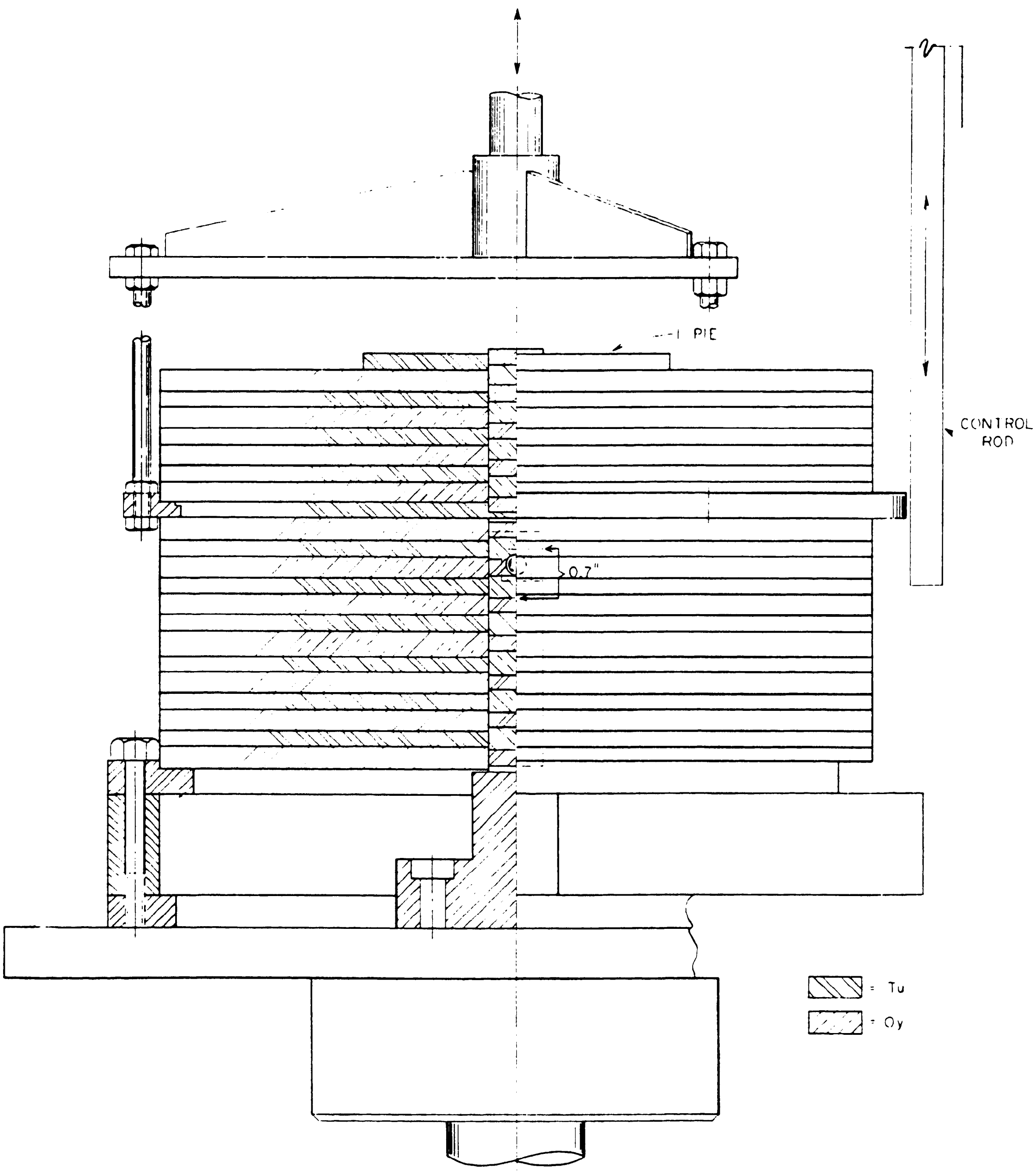

FIG. 1. Jemima assembly with 53-1/2% average U-235 concentration.

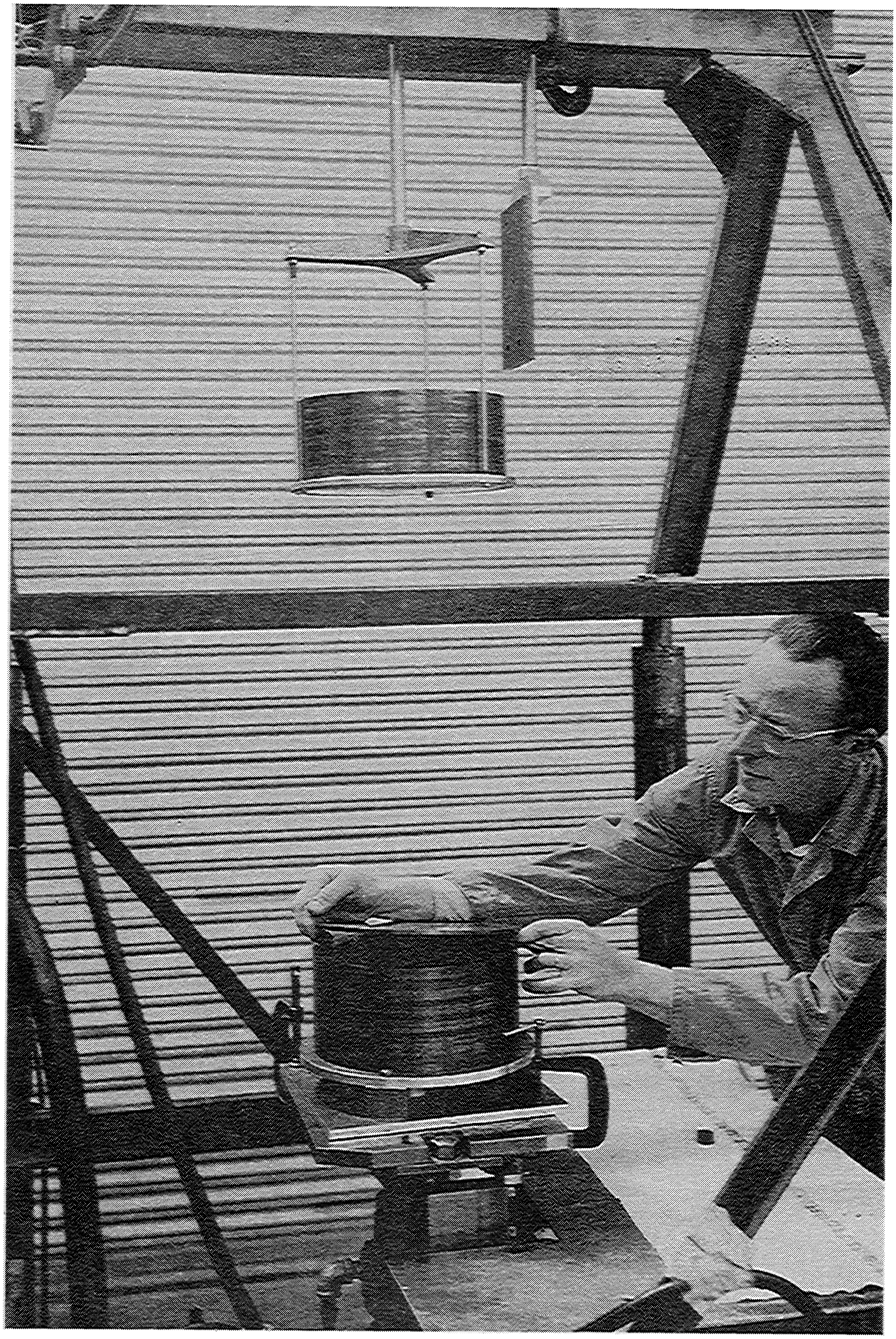

FIG. 2. Typical Jemima assembly.

2. Types of Measurement

Critical Mass: Each delayed critical configuration was established, as usual, by following reciprocal central source multiplication (1/M) as the Oy-Tu stack was built up. All-Tu mock-ups were used for unmultiplied counts. Once delayed critical conditions were established, the over-all value of the vernier control and effects of perturbations, such as the addition of a Tu pie or removal of material from the axial hole, were estimated in $\Delta(1/M)$ units and in cents (where 100 cents is the reactivity interval between delayed critical and prompt critical). The reactivity increments in cents were obtained from period measurements interpreted by means of the inhour equation and delayed neutron data of Hughes, et al.[(1)]

Incidental neutron reflection effects, primarily from the support at the base of each assembly, were estimated by observing the change in critical mass when a similar structure was added to the top of the stack. With this information, the observed critical mass values could be corrected to correspond to truly untamped cylinders.

For an estimate of the effect of gaps on the average density of an assembly, the actual height of a stack of 8 Oy

[(1)] Delayed Neutrons from Fission of U^{235}; Hughes, Dabbs, Cahn, and Hall; Phys. Rev. 73, 111, 1/15/48.

and 23 Tu plates was compared with the sum of the thicknesses. The observed height was 8.00" against 7.95 +", which corresponds to a density deficiency of $\sim$ 0.6%.

Rossi α: The value of α, the decay coefficient for prompt neutron chains, was determined for each assembly at delayed critical. Measurements were made by the statistical method described in LA-744.[2] In some cases, the detector used was an external anthracene crystal with photomultiplier and in other cases it was an Oy spiral fission chamber imbedded in the axial hole of the active cylinder.

Spectral Indices: Relative fission rates of 25, 37, and 28 detectors, when properly normalized, were used to define roughly the neutron spectra of the various assemblies. For some irradiations, 25 and 28 and, in one case, 37 foils were imbedded in the axial hole and for others, they were placed on the surface of the stack. After standard exposures, measurements of the gamma-activities of fission fragments were assumed to give the relative number of fissions in the various foils. With known sample weight correction, values could be reduced to fission rate per atom of detector at a given assembly power level. A special series of measurements of this type was designed to show the dependence of fission rates upon local Oy-Tu inhomogeneities.

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[2] LA-744; Time Scale Measurements by the Rossi Method; Orndoff and Johnstone; 11/9/49.

There was an attempt to use a double fission chamber (7/8" d. x 1" long) within the active system to give 37/28 and, as a check, 25/28 fission rate ratios. Actually, only the variations of ratios from one assembly to another were obtained. Finally, absolute determinations of the 25/28 fission rate ratio at the center of each of the principal assemblies were made from radiochemical analyses[3] of irradiated samples.

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[3] These analyses were made by J. Sattizahn of Group J-11 methods are outlined in LA-1566, Collected Radiochemical Procedures; Kleinberg; 2/1/53.

3. Characteristics of Oy (53-1/2%) Assemblies

The assemblies with an average U-235 concentration of 53-1/2% consisted of stacked pairs of Oy and Tu plates (Oy at the bottom). The specific Oy plates used (each 10.50" OD x 0.875" ID x 8.00 mm thick) averaged 93.4_1% in U-235 concentration and 8.354 kg in weight. The Oy fillers for the holes in these plates (0.87" diam. x 8.00 mm thick) each weighed 0.058 kg. The Tu plates (10.50" OD x 0.875" ID x 6.00 mm thick) averaged 6.364 kg in weight and the corresponding Tu fillers (0.87" diam. x 6.00 mm thick) were 0.042 kg each.

With the 7/8" axial hole properly filled, the actual critical configuration was 11 Oy-Tu pairs minus $\sim$ 7/8 of the top Tu plate (i.e., minus 7 Tu pie sections). This stacking is illustrated in Figure 1. Each Tu pie section contributed 24.6 cents or 0.00181 $\Delta(1/M)$ units to the reactivity, thus $\Delta(1/M) = 0.0074$ corresponds to 100 cents, the interval between delayed critical and prompt critical. Incidental neutron reflection by the support at the base of the stack (platen effect) contributed $\Delta(1/M) = 0.0099$ to the reactivity.

Emptying the 7/8" axial hole changed the observed critical configuration to nearly 11 Oy-Tu pairs. For this situation, it is estimated that the correction for platen effect is reduced to $\Delta(1/M) = 0.0082$ as the result of increased stack length. Figure 3 gives 1/M vs. number of Oy-Tu pairs, and Figure 4 shows the observed changes in 1/M for each added plate (and for Tu in place of Oy) as this stack was built up from 9 Oy-Tu pairs to critical. These data provide a means of converting from $\Delta(1/M)$ units to fraction of an Oy-Tu pair at a given stack height; e.g., to convert a platen correction to an equivalent increase in stack height.

Critical conditions for the truly untamped Oy (53-1/2) assemblies (i.e., after platen correction) are given in Table I; also listed are values for the Rossi alpha at delayed critical. In Table II, are 37/28 and 25/28 activation ratios at positions near the center of the system (where these ratios are practically independent of position). Figures 5, 6, 7, 8, and 9 show relative activation rates of 25 and 28 detectors and 25/28 ratios as functions of axial position and position on the assembly surface.

The final series of activation measurements (made in 1954 with a modified γ-counter) provides a basis for estimating the influence of Oy-Tu inhomogeneity upon 25/28 fission cross section ratio. A number of the 8 mm thick Oy and 6 mm thick glory hole fillers were rearranged so that foils (1/2" diam.) for γ-counting were contacted by three different types of disk pairs: Oy and Tu; Oy and Oy; and Tu and Tu. As

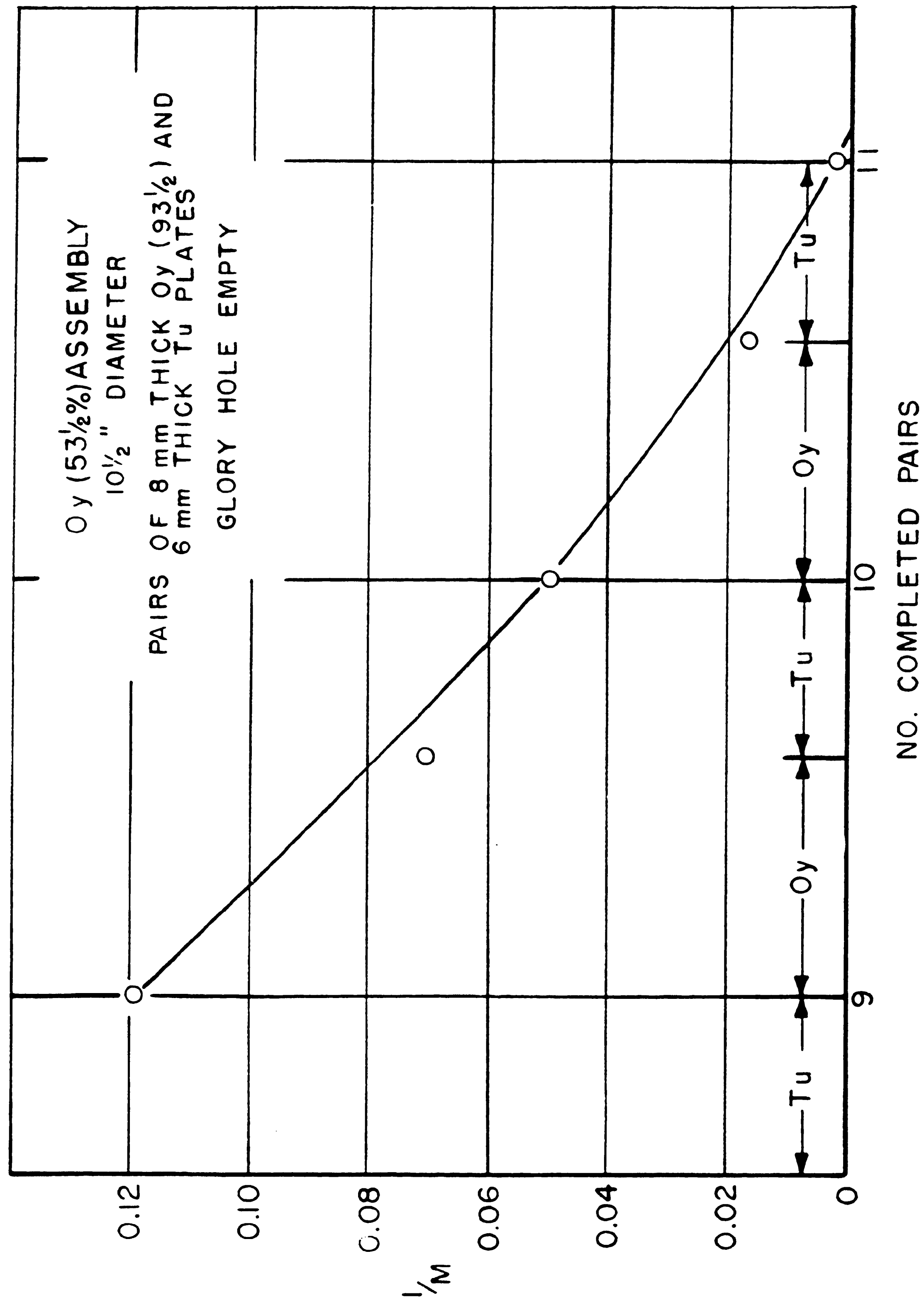

FIG. 3. Reciprocal multiplication vs. number of Oy-Tu pairs as the Oy (53-1/2) delayed critical configuration is approached.

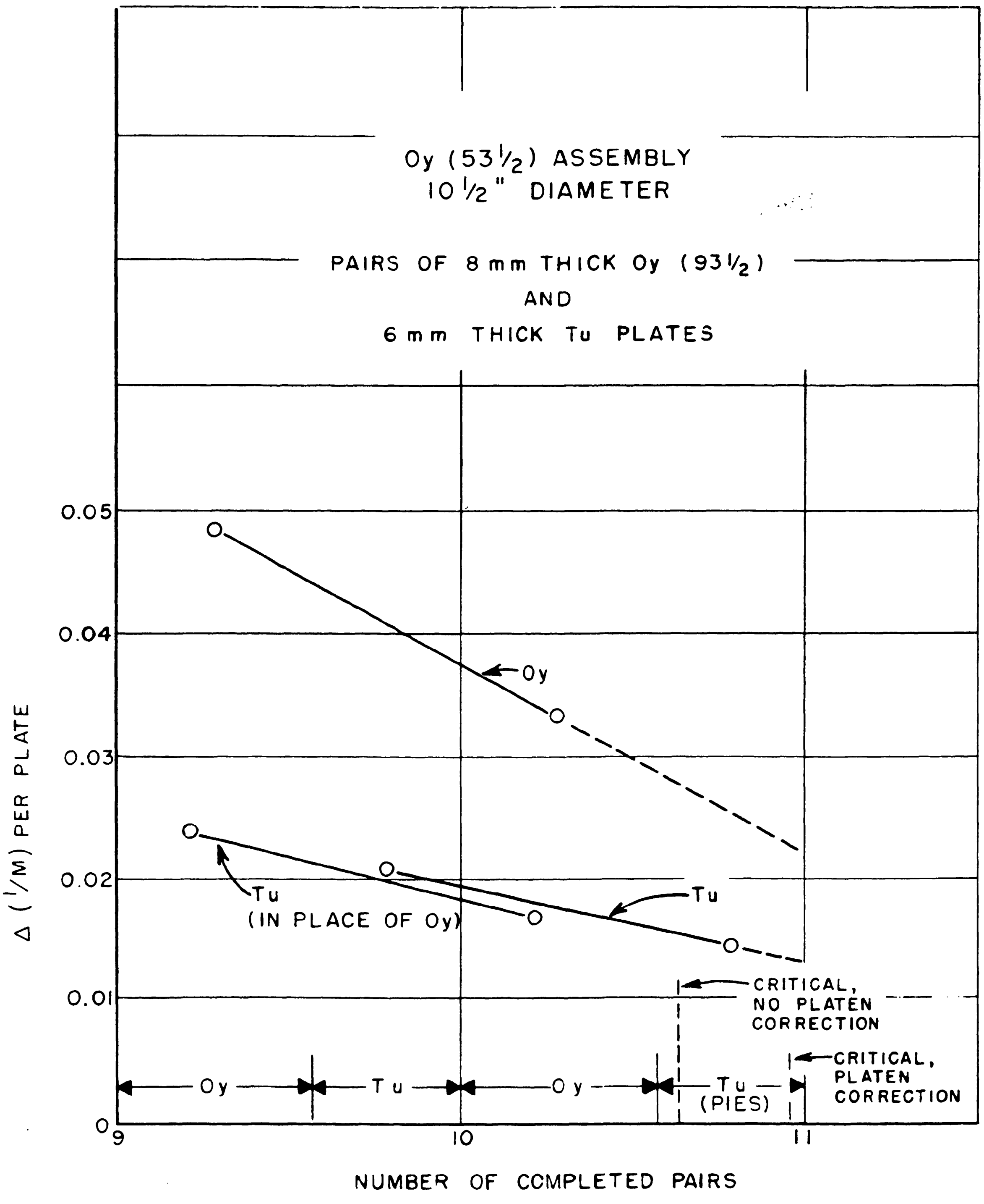

FIG. 4. Reactivity contribution of each plate as the Oy (53-1/2) assembly is built up from 9 to 11 pairs.

TABLE I.

CHARACTERISTICS OF BARE OY (53-1/2) CYLINDERS AT DELAYED CRITICAL

Average U-235 concentration	53.6% (atomic)
Estimated mean density	18.7 gm/cm^3
Axial hole filled:	
critical mass (± 0.5%)	91.94 kg Oy (93.41) 70.02 kg Tu (10.93 Oy-Tu pairs)
dimensions of critical cylinder	10.50" diam. ~ 6.10" height
Axial hole empty:	
critical mass (± 0.5%)	93.98 kg Oy (93.41) 71.60 kg Tu (11.25 Oy-Tu pairs)
dimensions of critical cylinder	10.50" OD x 0.875" ID ~ 6.28" height
Over-all effect of control plate	~ 27 cents
Rossi α at delayed critical:	
external anthracene detector	-0.63×10^6 sec^{-1}
same with mock platen	-0.62×10^6 sec^{-1}
external B^{10} counter (statistics poor)	-0.65×10^6 sec^{-1}

TABLE II.

SPECTRAL INDICES OF BARE OY (53-1/2) CYLINDER

γ-counting of irradiated foils

(central ratios, assuming γ-activity proportional to fissions)

from Figure 9:	$\sigma_f(25)/\sigma_f(28)$	= 9.6
from Figure 10:	$\sigma_f(25)/\sigma_f(28)$	= 8.9
	$\sigma_f(37)/\sigma_f(28)$	= 5.3

Radiochemical analysis

dist. above center (in.)	$\frac{\sigma_f(25)}{\sigma_f(28)}$	$\frac{\sigma_f(49)}{\sigma_f(25)}$	$\frac{\sigma_{n,\gamma}(28)}{\sigma_f(28)}$	$\frac{\sigma_{n,2n}(28)}{\sigma_f(28)}$
irradiation of 1/18/54:				
0.14	$(8.3_9, 8.9_9)^{(1)}$	$(1.56, 1.46)^{(1)}$	0.73_7	0.048_8
1.42	8.3_3	1.30_0	0.75_8	0.048_1
2.70	8.1_5	1.48_8	0.69_7	0.049_7
irradiation of 1/19/54:				
0.05	8.9_4	1.34_5	0.81_6	--

At center:

date:	5/11/53	1/19/54	1/18/54	1/18/54	Average
$\sigma_f(25)/\sigma_f(28)$:	8.38	8.95	$8.39^{(1)}$	$8.99^{(1)}$	8.68 ± 0.20

(1) Extrapolation of central 25/28 from 1.42" and 2.70" (25 analysis lost).

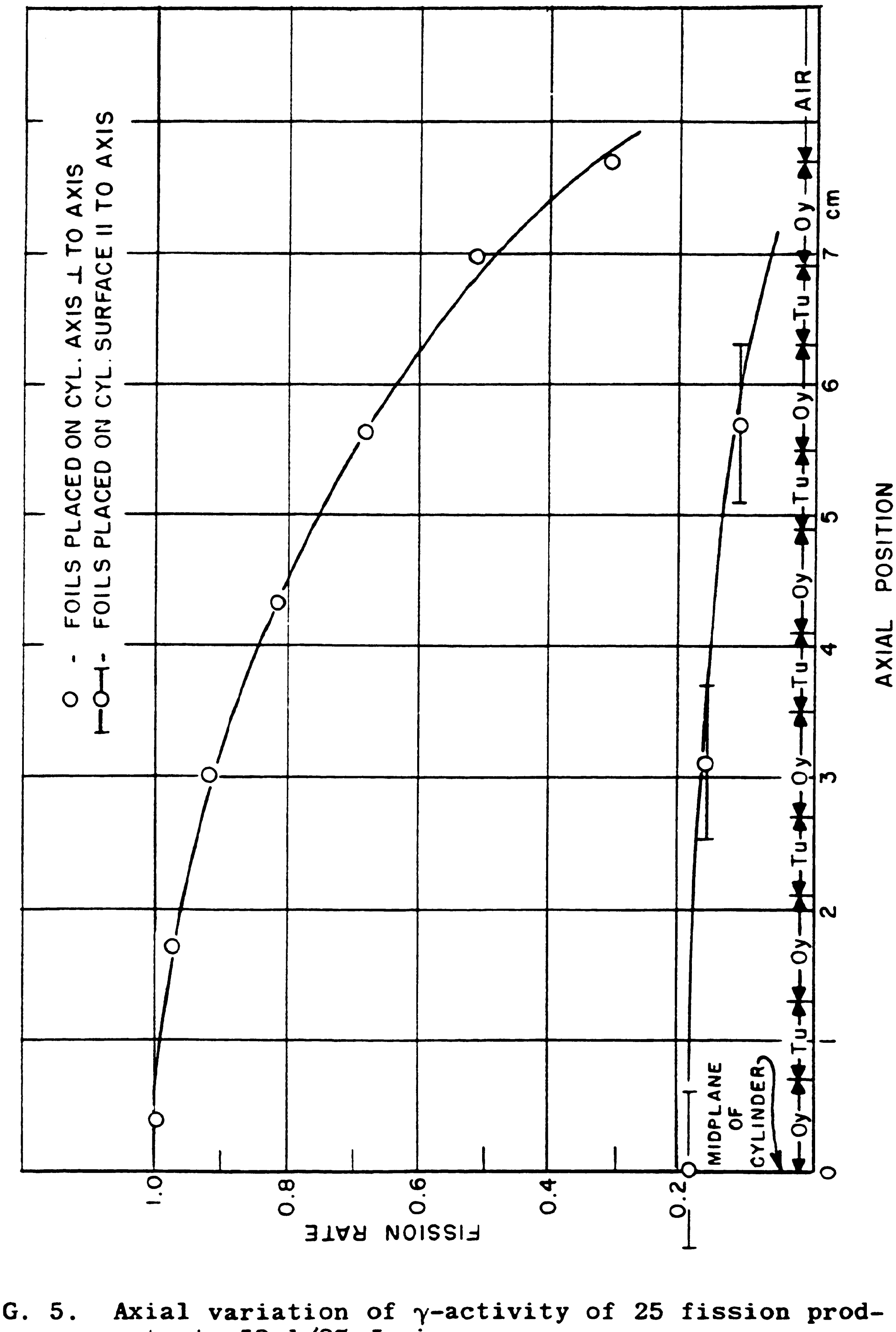

FIG. 5. Axial variation of γ-activity of 25 fission products in 53-1/2% Jemima.

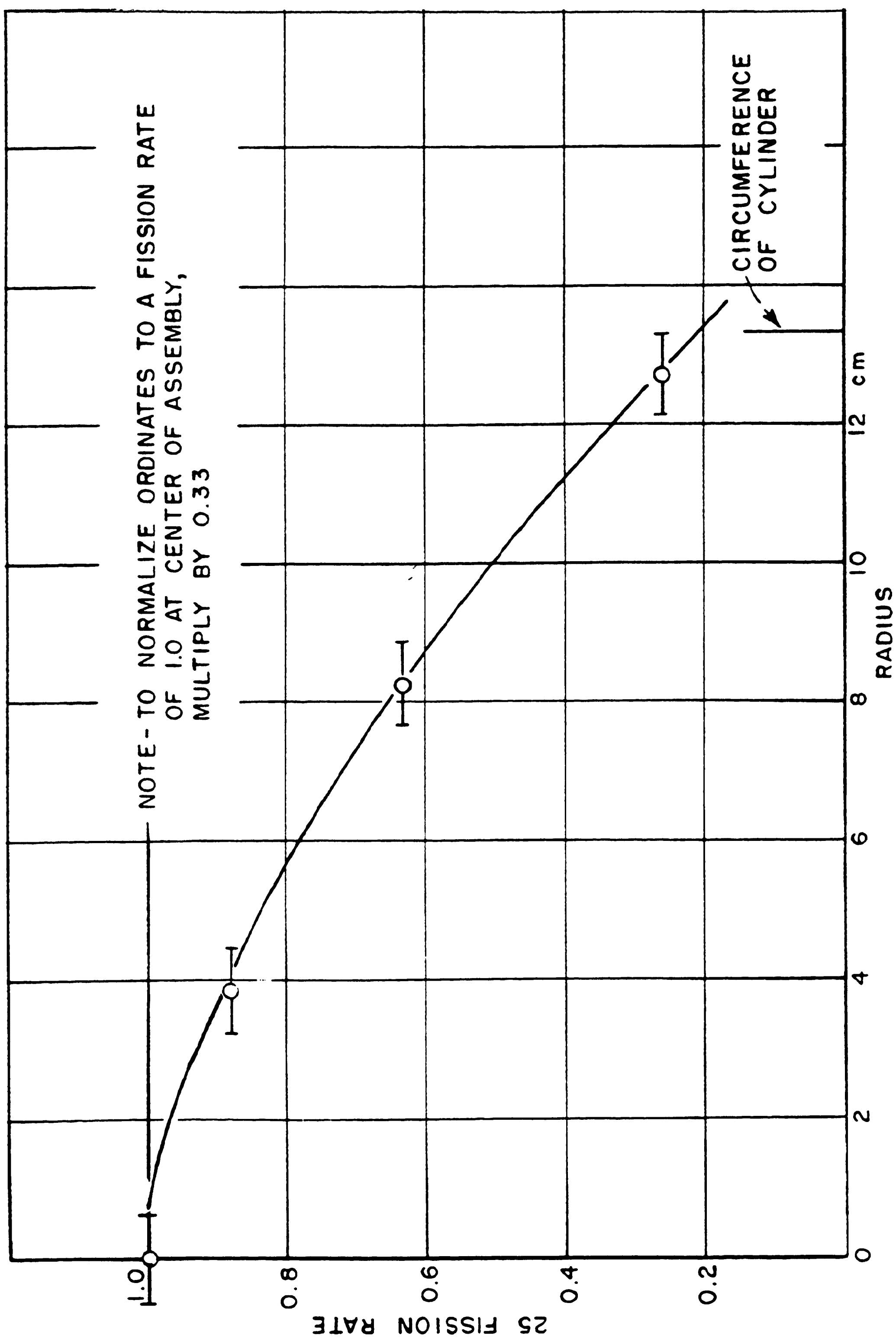

FIG. 6. Radial variation of γ-activity of 25 fission products across end of 53-1/2% Jemima.

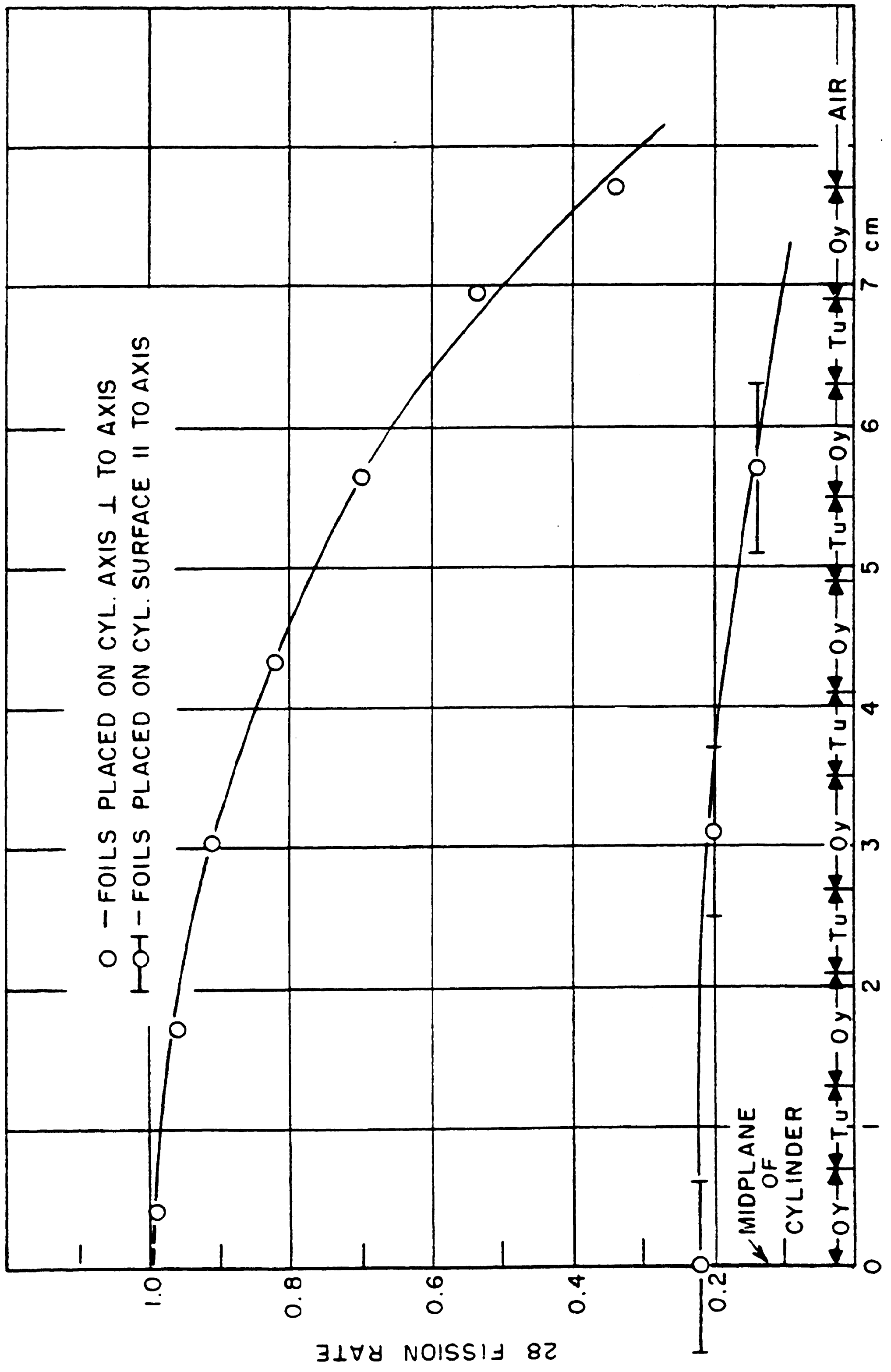

FIG. 7. Axial variation of γ-activity of 28 fission products in 53-1/2% Jemima.

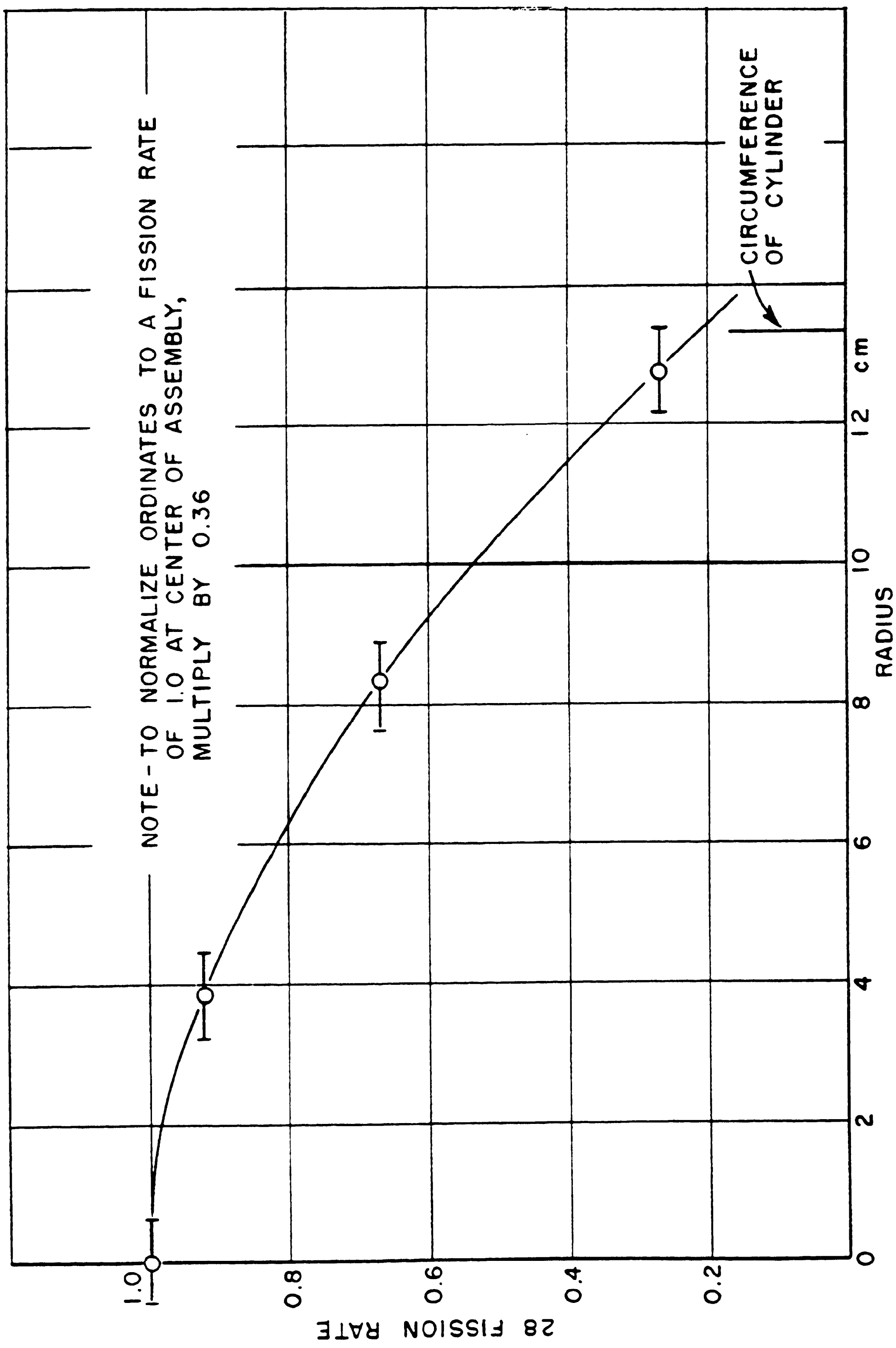

FIG. 8. Radial variation of γ-activity of 28 fission prod ucts across end of 53-1/2% Jemima.

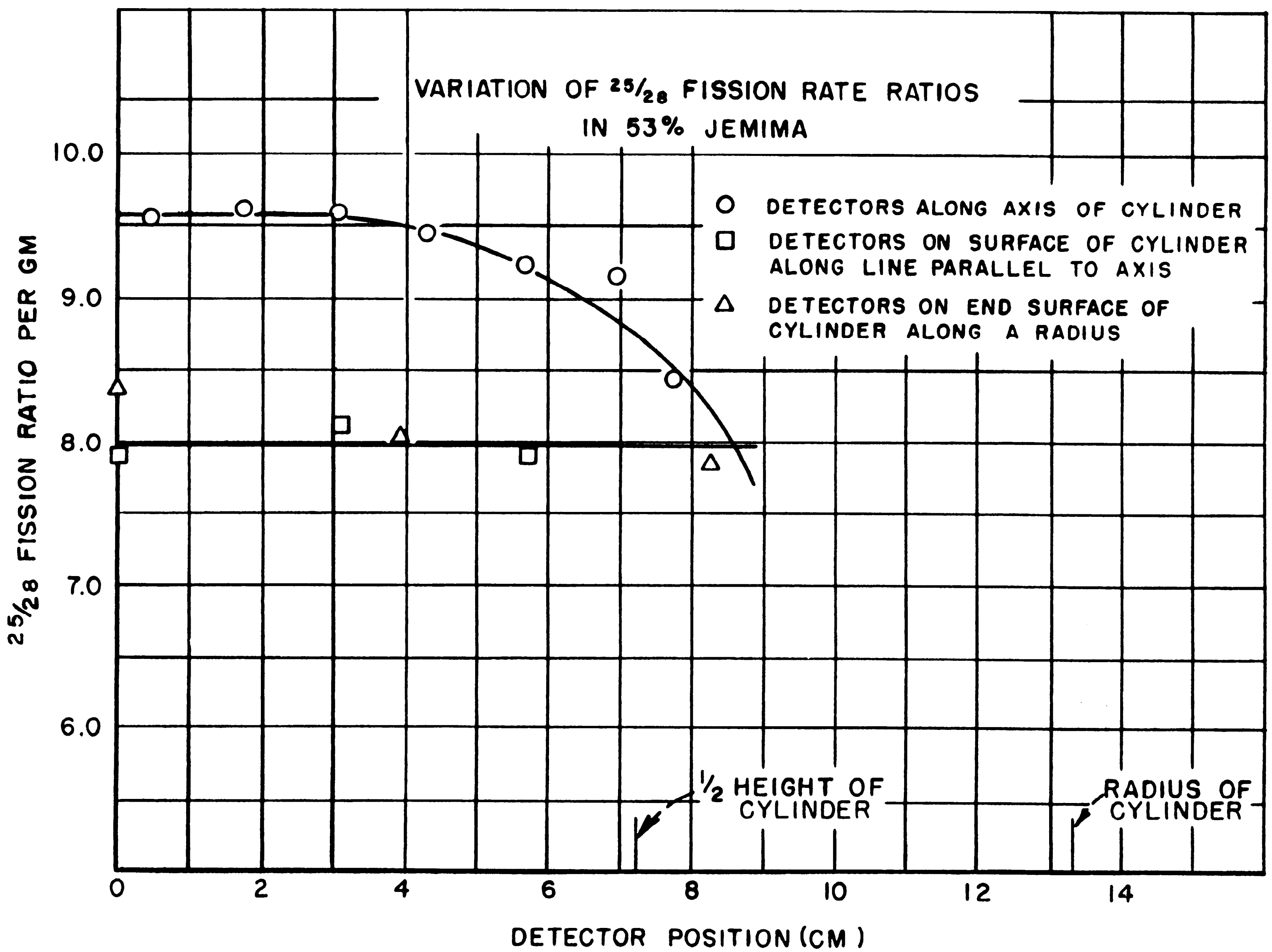

FIG. 9. Variation of 25/28 γ-activity ratios in 53-1/2% Jemima.

shown in Figure 10, the 25/28 ratio for foils between Tu disks averaged 6% high, and between Oy disks, 6% low, with respect to the value for foils between Tu and Oy. It may be noted that the central mean 25/28 ratio, 8.9, falls closer to the radiochemical value than did any earlier γ-counting determination. There is no direct check on the indicated value 5.3 for the 37/28 ratio.

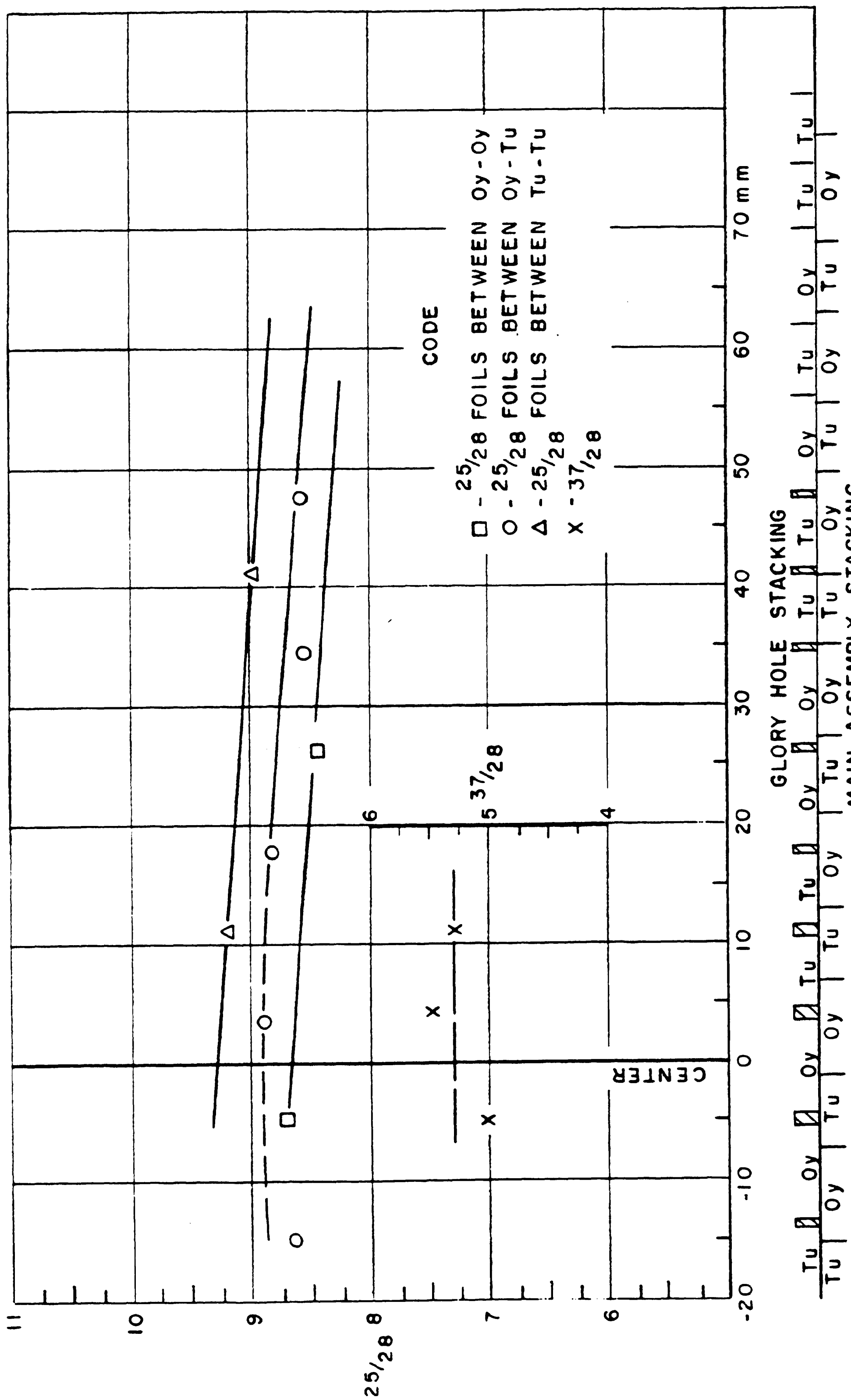

FIG. 10. Oy (53-1/2%) Assembly - Influence of local structure on 25/28 and 37/28 γ-activity ratios.

4. Characteristics of Oy (37-1/2%) Assemblies

For an average U-235 concentration of 37-1/2%, the basic unit was an Oy-Tu triplet consisting of an Oy plate sandwiched between two Tu plates. To approach critical, this unit was repeated. In this case the Oy plates had an average U-235 concentration of 93.4_3% and an average weight of 8.357 kg.

As illustrated in Figure 11, the actual critical configuration with the axial hole filled was 12 Oy-Tu triplets plus $\sim$ 1-3/8 Tu plates (plus 1 Tu plate and 3 Tu pies). The platen effect (measured with the axial hole empty) was estimated to be $\Delta(1/M) = 0.0041$.

With the 7/8" axial hole empty, the system was critical at 13 Oy-Tu triplets minus nearly 2 Tu pie sections. Under this condition, the reactivity contribution of each Tu pie section was determined to be 10.8 cents or 0.00062 $\Delta(1/M)$ units. The corresponding interval between delayed critical and prompt critical, $\Delta(1/M) = 0.0057$, is lower than observed for any other metal assembly, so may be suspect. The platen correction was measured as $\Delta(1/M) = 0.0035$. Figure 12 gives $1/M$ vs. number of Tu-Oy-Tu triplets, and Figure 13, the $\Delta(1/M)$ increments for each added plate as the stack was built up from 11 triplets to 13 triplets (minus).

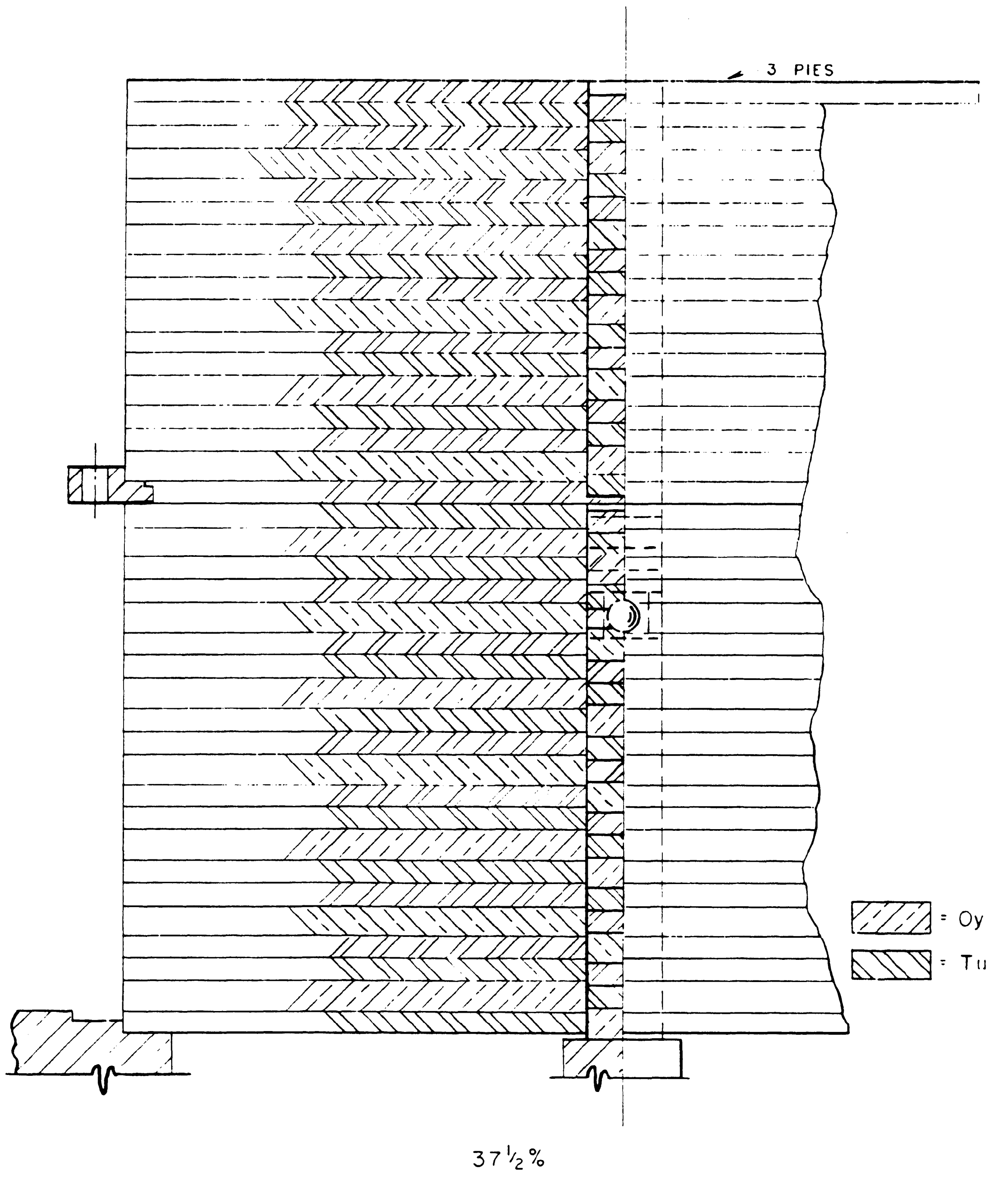

FIG. 11. 37-1/2% Jemima assembly.

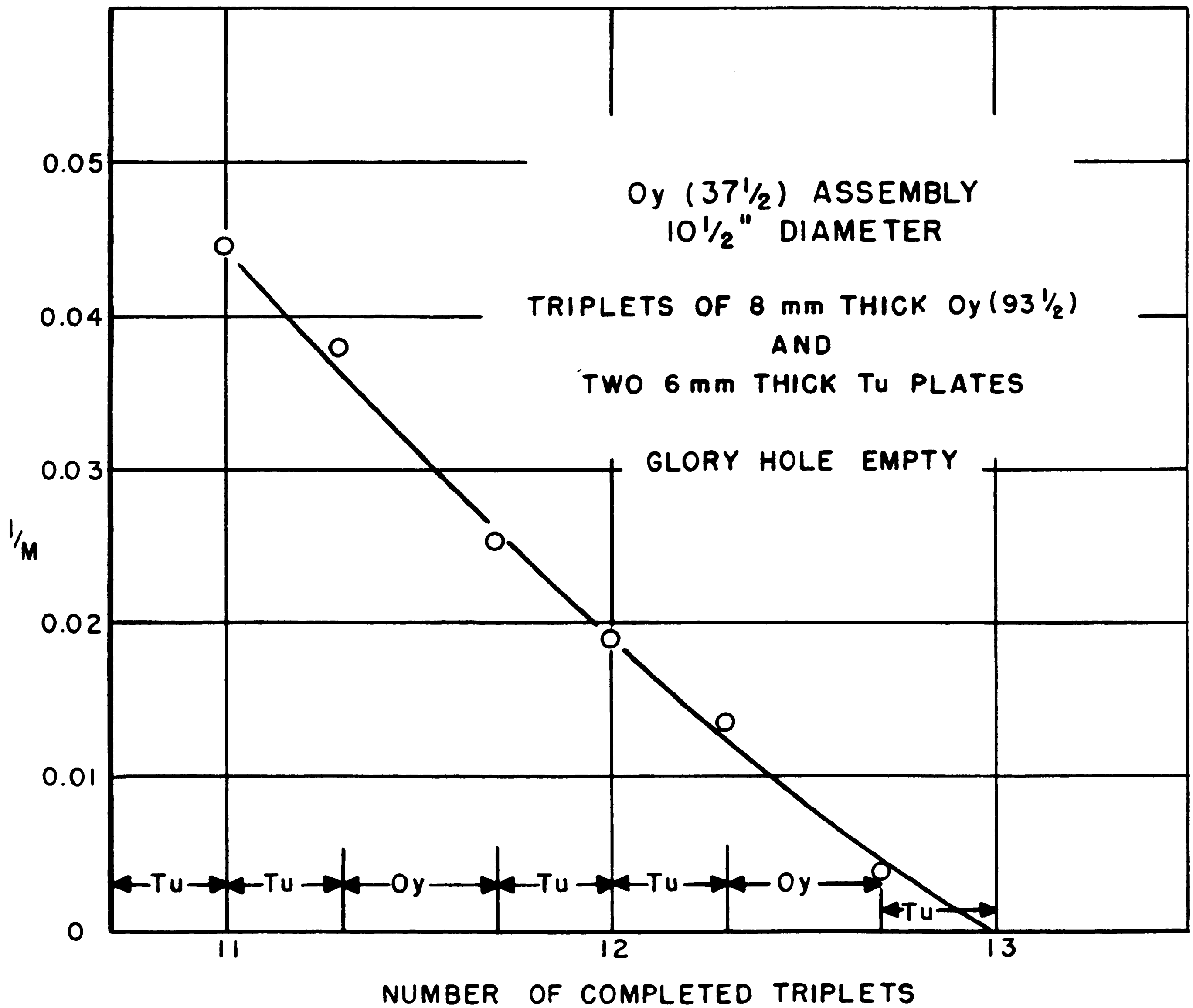

FIG. 12. Reciprocal multiplication vs. number of Tu-Oy-Tu triplets as the Oy (37-1/2) delayed critical configuration is approached.

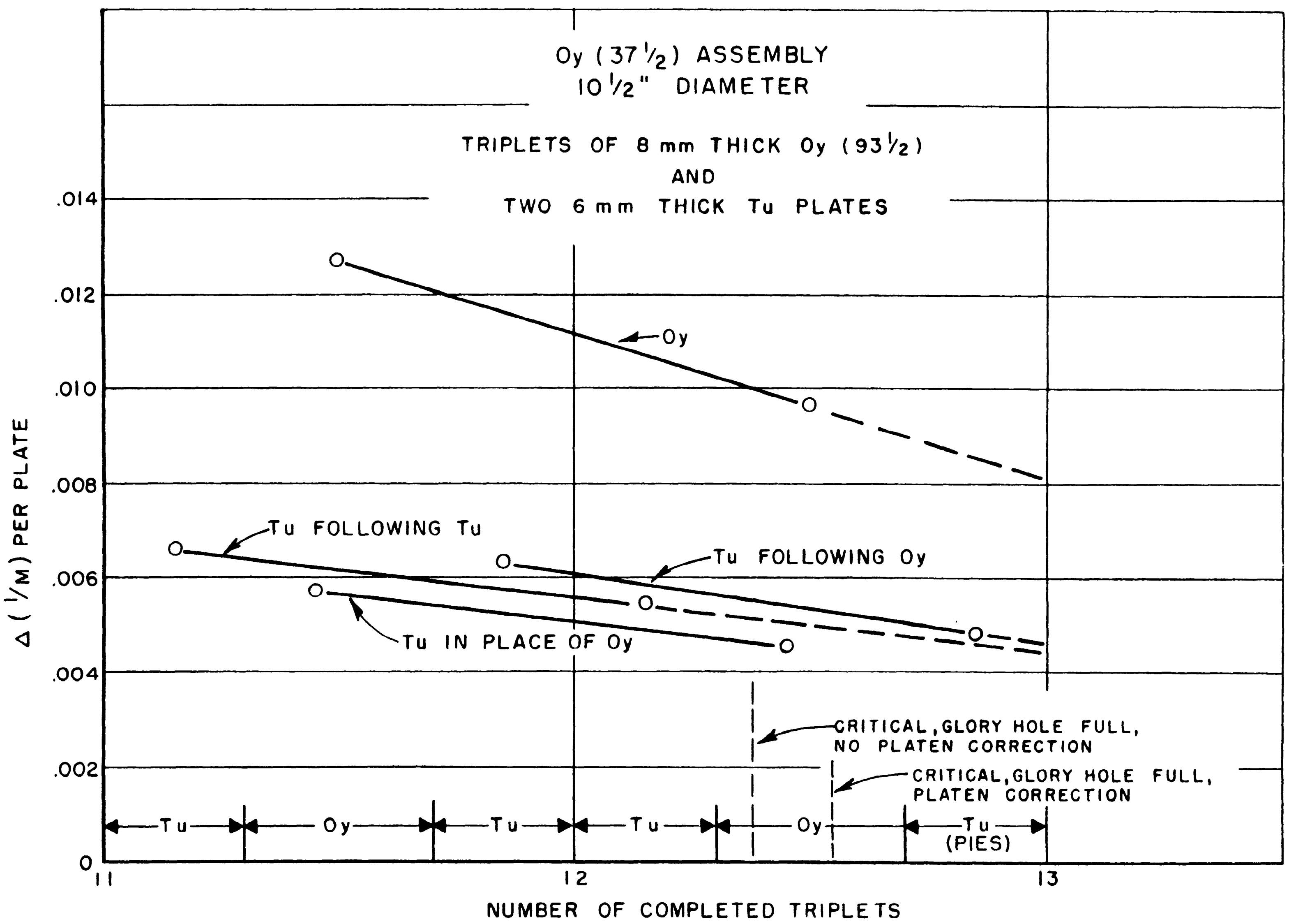

FIG. 13. Reactivity contribution of each plate as the Oy (37-1/2) assembly is built up from 11 to 13 triplets.

Listed in Table III, are critical conditions for the bare 37-1/2% assemblies (again, after the platen correction), Rossi α at delayed critical and a few reactivity changes resulting from the introduction of materials into a central cavity. Table IV gives activation ratios for the assembly with glory hole filled. Axial and surface variations of 25 and 28 fission rates and of 25/28 fission rate ratios are shown in Figures 14, 15, 16, 17, and 18.

TABLE III.

CHARACTERISTICS OF BARE OY (37-1/2) CYLINDERS AT DELAYED CRITICAL

Average U-235 concentration	37.7%
Estimated mean density	18.75 gm/cm^3
Axial hole filled:	
critical mass (± 0.5%)	105.86 kg Oy (93.43) 161.17 kg Tu (12.58 Oy-Tu triplets)
dimensions of critical cylinder	10.50" diam. $\sim$ 10.04" height
Axial hole empty:	
critical mass (± 0.5%)	109.90 kg Oy (93.43) 167.37 kg Tu (13.15 Oy-Tu triplets)
dimensions of critical cylinder	10.50" diam. $\sim$ 10.49" height
Over-all effect of control plate	$\sim$ 36 cents
Rossi α at delayed critical:	
external anthracene detector	$- 0.47 \times 10^6$ sec^{-1}
internal spiral Oy fission chamber	$- 0.46 \times 10^6$ sec^{-1}
Reactivity contributions of 1/2" x 1/2" cylindrical samples in central cavity:	
Oy (94)	52 cents/mole
Tu	4 cents/mole
Au (3/4" diam. sphere)	- 4 cents/mole
90% B^{10} + 10% B^{11}	- 23 cents/mole
CH_2(3/16" thick annular space about sample)	24 cents/mole
CH_2(3/16" thick Tu cylinder about sample)	26 cents/mole
CH_2(3/16" thick Oy cylinder about sample)	31 cents/mole

TABLE IV.

SPECTRAL INDICES OF BARE OY (37-1/2) CYLINDER

<u>Comparison fission chamber</u>

(central ratios)

Ratio of $\sigma_f(25)/\sigma_f(28)$ for Jemima 37-1/2% to that for Jemima 53-1/2% = 1.24

Ratio of $\sigma_f(37)/\sigma_f(28)$ for Jemima 37-1/2% to that for Jemima 53-1/2% = 1.11

(individual ratios unreliable)

<u>γ-counting of irradiated foils</u>

(central ratio, assuming γ-activity proportional to fissions)

from Figure 18: $\sigma_f(25)/\sigma_f(28)$ = 10.9[(1)]

<u>Radiochemical analysis</u>

<u>At center</u>:

date:	6/10/52	5/4/53	5/27/53	6/9/53
$\sigma_f(25)/\sigma_f(28)$:	10.8[(2)]	9.77[(1)]	10.01[(1)]	9.86[(1)]

[(1)]Corrected + 2% to adjust from Oy-Tu interface to average spectrum.

[(2)]Corrected - 5% to adjust from complete Tu surroundings to average spectrum.

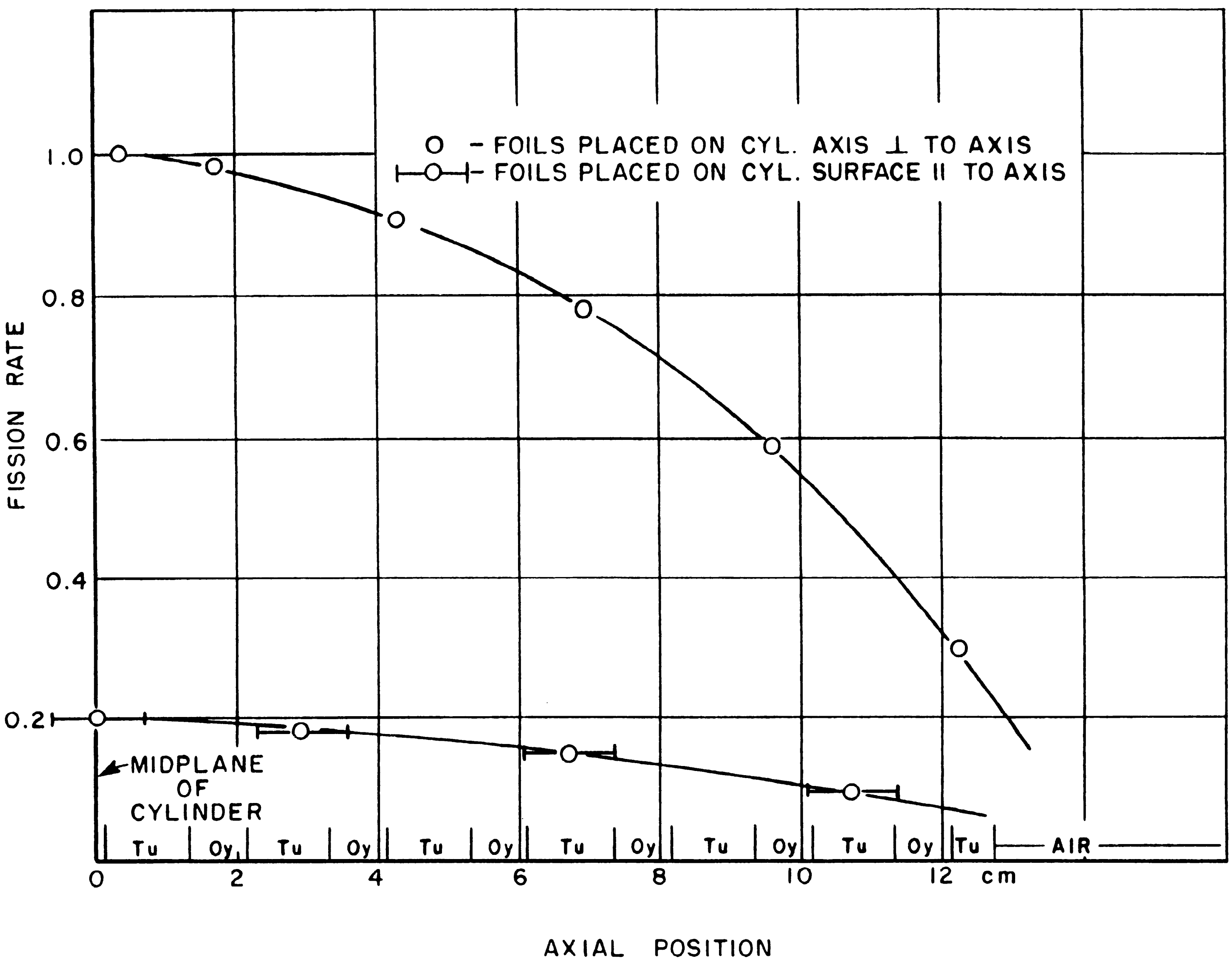

FIG. 14. Axial variation of γ-activity of 25 fission products in 37-1/2% Jemima.

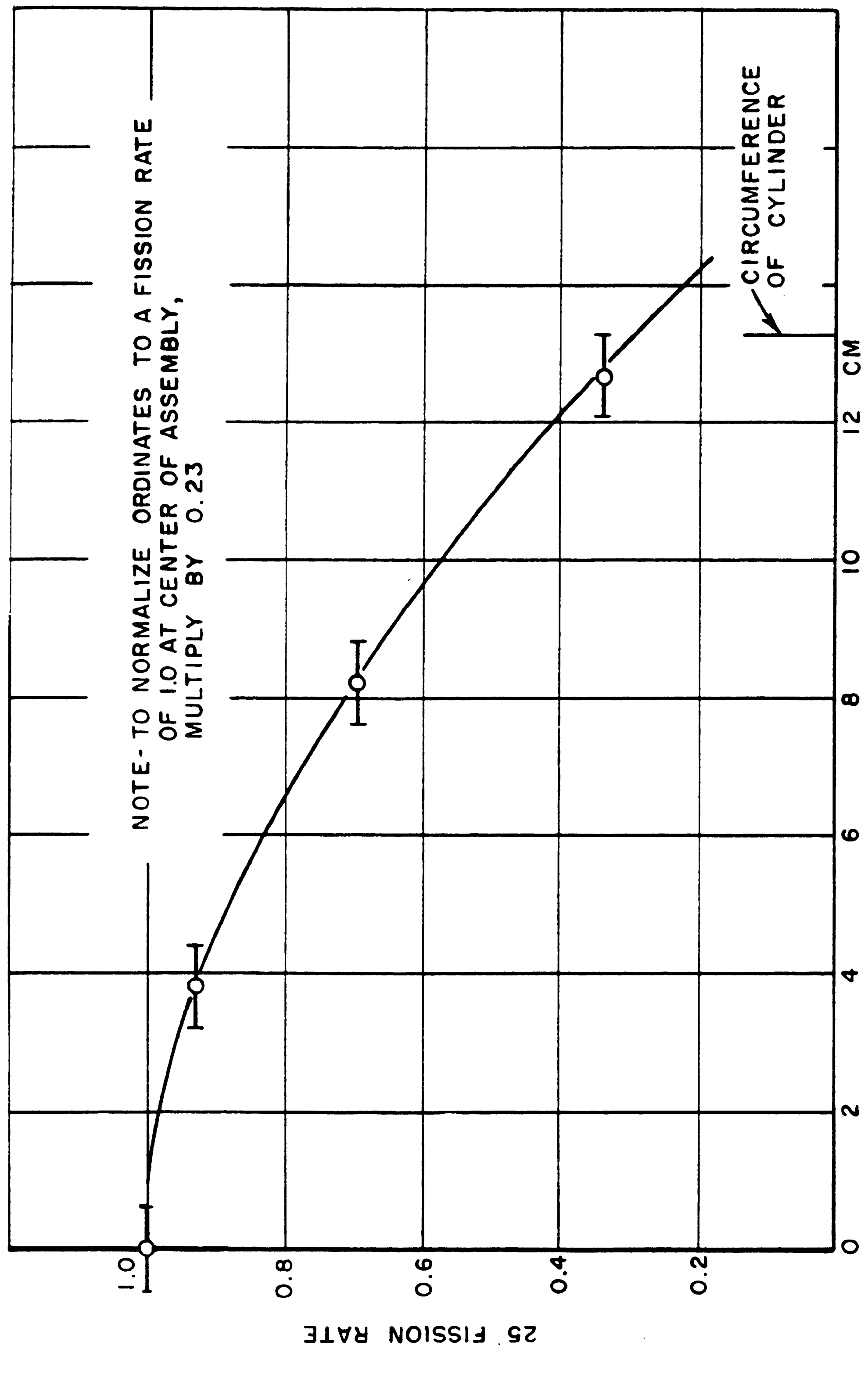

FIG. 15. Radial variation of γ-activity of 25 fission products across end of 37-1/2% Jemima.

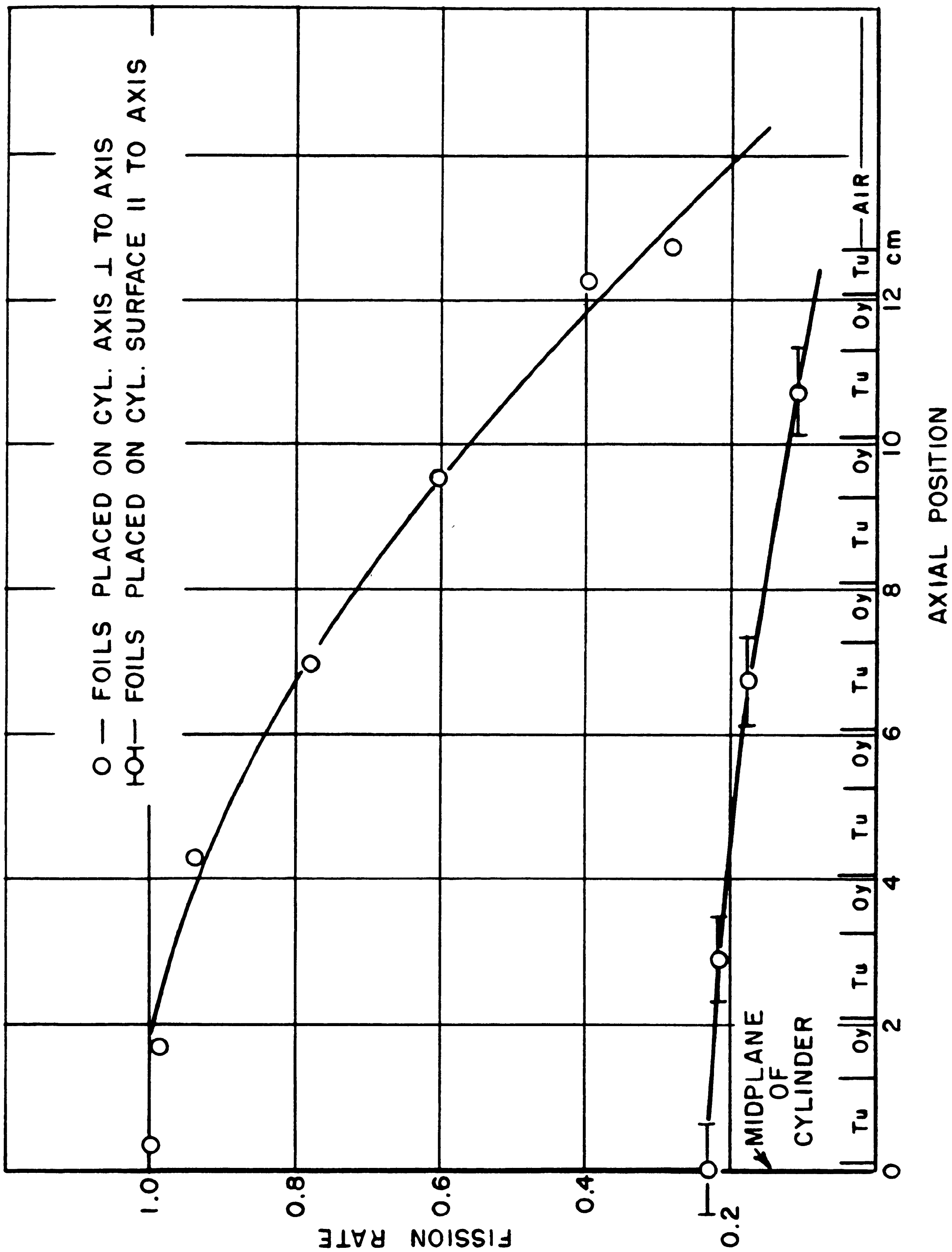

FIG. 16. Axial variation of γ-activity of 28 fission products in 37% Jemima.

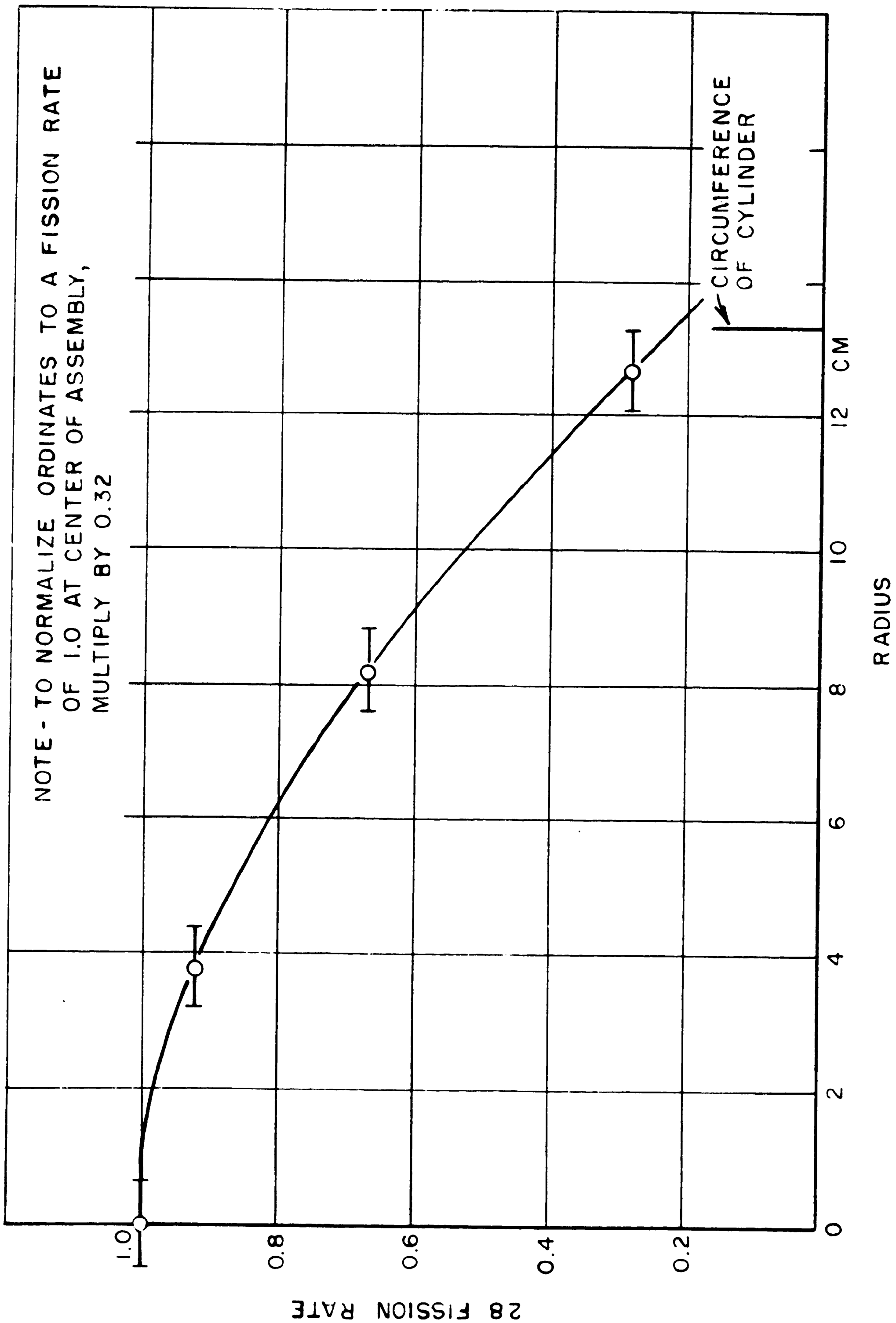

FIG. 17. Radial variation of γ-activity of 28 fission products across end of 37-1/2% Jemima.

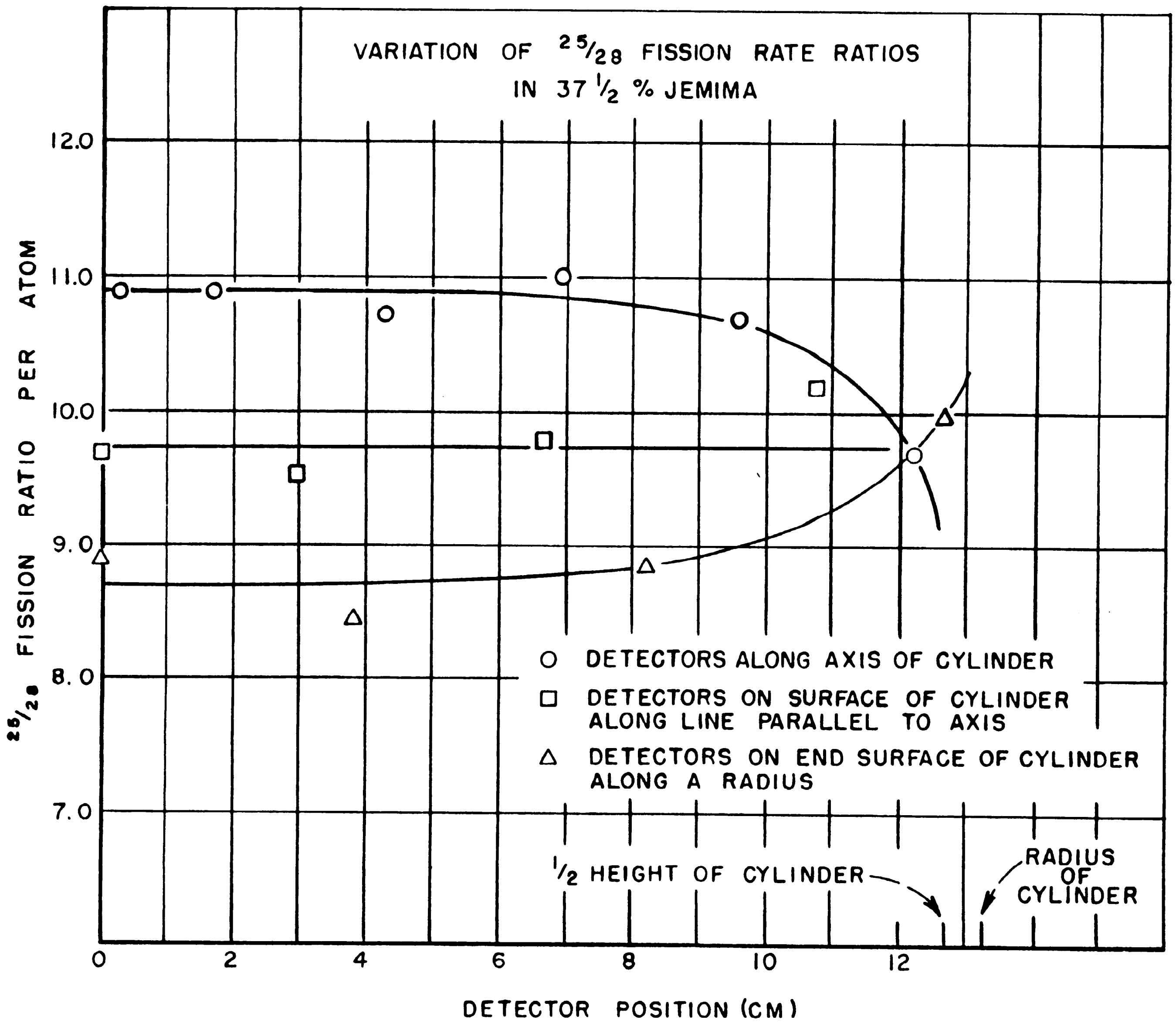

FIG. 18. Variation of 25/28 γ-activity ratios in 37-1/2% Jemima.

5. Characteristics of the Oy (29%) Assembly

There were insufficient plates to make a critical assembly of repeated Oy-Tu quadruplets, three Tu plates per Oy plate. However, a system of the appropriate average U-235 concentration, 29%, was improvised by covering a basic stack of quadruplets with small Oy and Tu blocks in the proper proportion. As indicated by Figure 19, 12 Oy-Tu quadruplets (3 Tu plates per Oy plate, 1 Tu at the bottom) were stacked with 0.500" layers of Tu blocks substituted for pairs of Tu plates in the two upper quadruplets. A 1/2" thick layer of 1/2 x 1/2 x 1/2" and 1/2 x 1/2 x 1" Oy and Tu blocks (in the appropriate proportion) was added to the cylindrical surface of this stack, except on areas about the support for the upper portion of the system and the top quadruplet. Finally, to attain critical, two 1" thick layers of Oy and Tu blocks were added to the top of the assembly, the first of these layers containing 54.0 in.^{3} Tu and 26.0 in.^{3} Oy and the abbreviated top layer containing 16.9 in.^{3} Tu and 8.4 in.^{3} Oy.

The observed critical mass was 129.32 kg Oy at an average U-235 concentration of 93.5%, plus 294.25 kg Tu (423.6 kg Oy - 29%). With the $\Delta(1/M)$ contributions of the top three Oy-Tu units as a guide (Figure 20), this critical mass

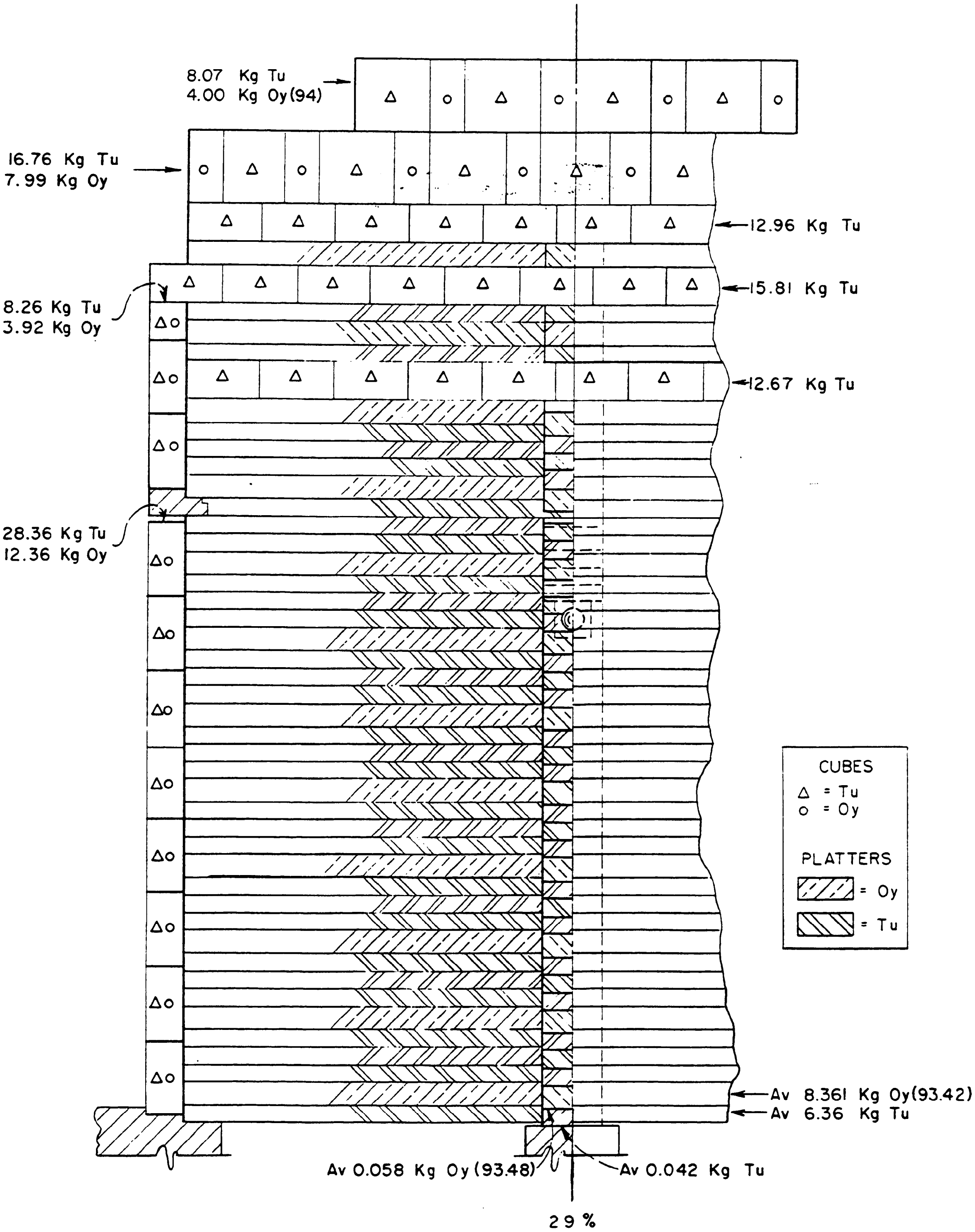

FIG. 19. 29% Jemima assembly.

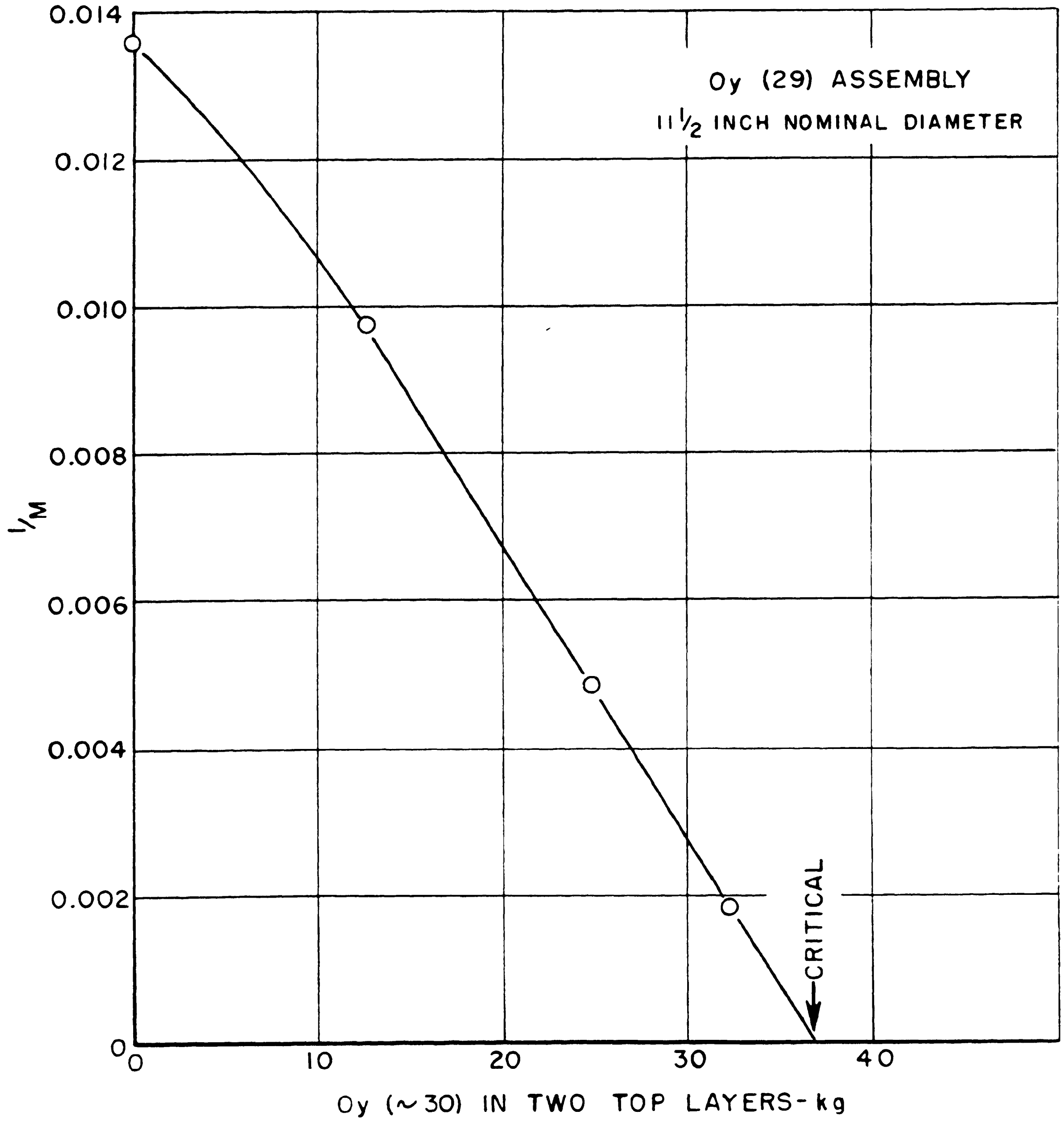

FIG. 20. Reactivity contributions of 2 top units of the Oy (29) assembly as observed during build-up.

was corrected to that of a true cylinder 11.42" in diam. (to account for imperfect packing of the cylindrical layer of blocks), and allowance was made for platen effect (estimated to be 4.4 kg Oy 29%). The resulting critical conditions for a bare cylinder are given in Table V.

TABLE V.

CHARACTERISTICS OF BARE OY (29) CYLINDER AT DELAYED CRITICAL

Average U-235 concentration	29.0%
Estimated average density	18.8 gm/cm^3
Critical mass (± 1%)	424 kg Oy (29.0)
Effective critical dimensions:	
diameter	11.42"
height	13.45"
Rossi α at delayed critical	$- 0.37 \times 10^6$ sec^{-1}
25/28 fission ratio, center, β -counting (old method)	12.9 to 13.7

6. Correlations with 25 Concentration

Values of critical mass, Rossi alpha at delayed critical and fission ratios are listed in Table VI for the various critical assemblies of bare uranium metal. Data for Godiva, the Oy (93.7) critical sphere, are obtained from LA-1614 and LA-1653.[4] Equivalent spherical critical masses for the Jemima assemblies are obtained by applying the shape corrections of LA-1155[5] for bare oralloy systems. Figures 21 and 22 show corrected critical mass, Rossi alpha, and fission ratios as functions of 25 concentration. To the first approximation, at least, these functions may be expressed:

$$\text{spherical critical mass} = \text{const. } c^{-1.71},$$

$$\text{Rossi alpha} = \text{const. } c^{0.92},$$

$$\sigma_f(25)/\sigma_f(28) = \text{const. } c^{-0.60},$$

$$\text{and } \sigma_f(37)/\sigma_f(28) = \text{const. } c^{-0.29},$$

where c is the 25 concentration. The relationship between

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[4] LA-1614; Lady Godiva: An Unreflected Uranium-235 Critical Assembly; Peterson; 9/53;
LA-1653; Neutron Detector Traverses in the Topsy and Godiva Critical Assemblies; Linenberger, Lowry; 4/54.

[5] LA-1155; OY Shape Factor Measurements; Josephson, Paine, Woodward; 8/8/50.

TABLE VI.

CRITICAL PARAMETERS AT VARIOUS U-235 CONCENTRATIONS

	Godiva	Jemima 53-1/2%	Jemima 37-1/2%	Jemima 29%
average U-235 concentration	93.7 %	53.6 %	37.7 %	29.0%
critical mass (kg total)				
observed		162.0	267.0	424
corrected to sphere	52.25	140	245	377
Rossi alpha (sec^{-1})	-1.08×10^6	-0.63×10^6	-0.465×10^6	-0.37×10^6
$\sigma_f(25)/\sigma_f(28)$				
radiochemical	6.18	8.68	10.11	--
γ-counting	6.54	9.6,8.9	10.9	(12.9-13.7[1])
comparison chamber	6.2	a[2]	1.24a	--
$\sigma_f(37)/\sigma_f(28)$				
γ-counting	4.49	5.3	--	--
comparison chamber	4.8	b[2]	1.11b	--

(1) Old β-counting method.

(2) Constants.

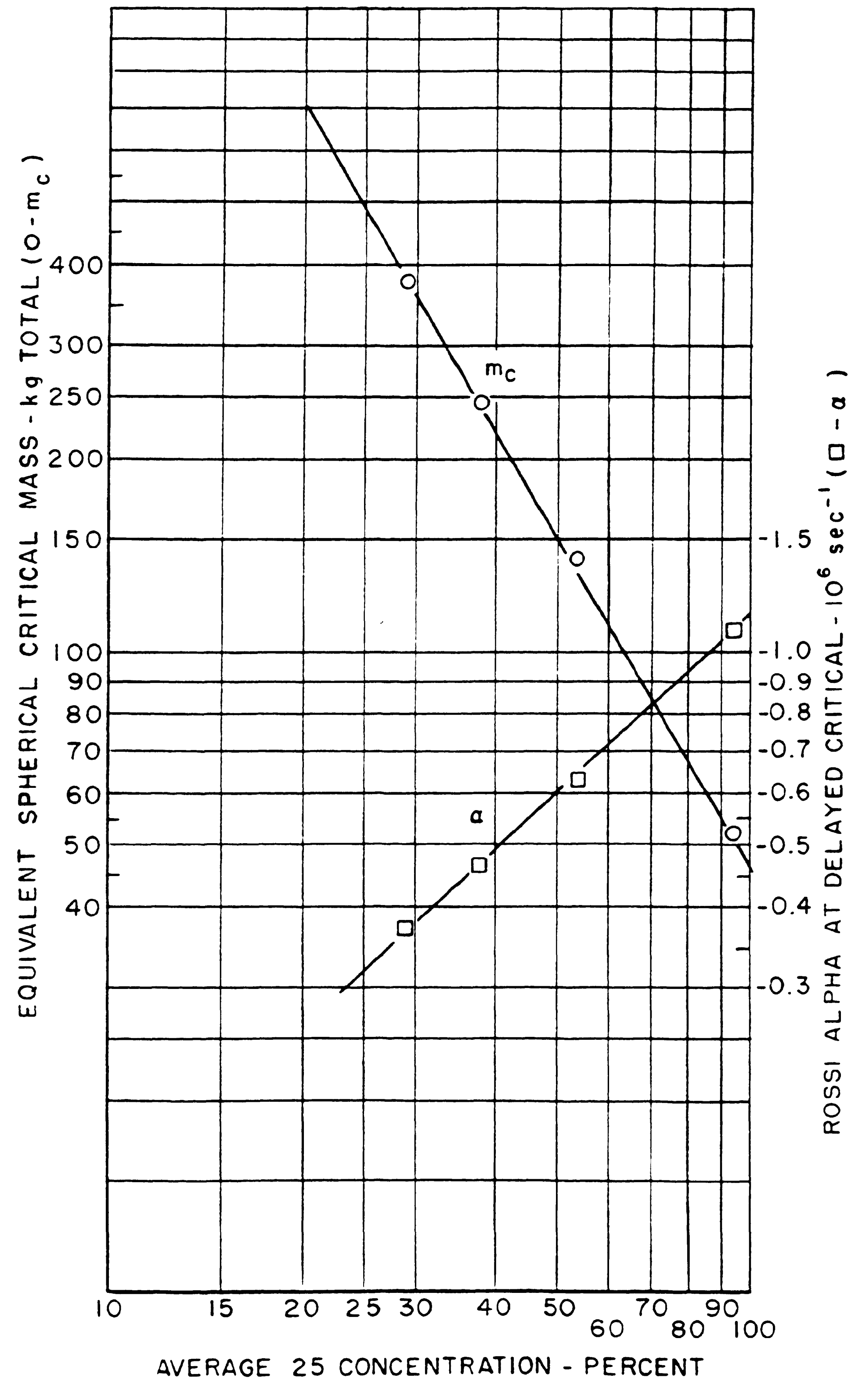

FIG. 21. Critical mass (corrected to spherical shape) and Rossi alpha as functions of U-235 concentration.

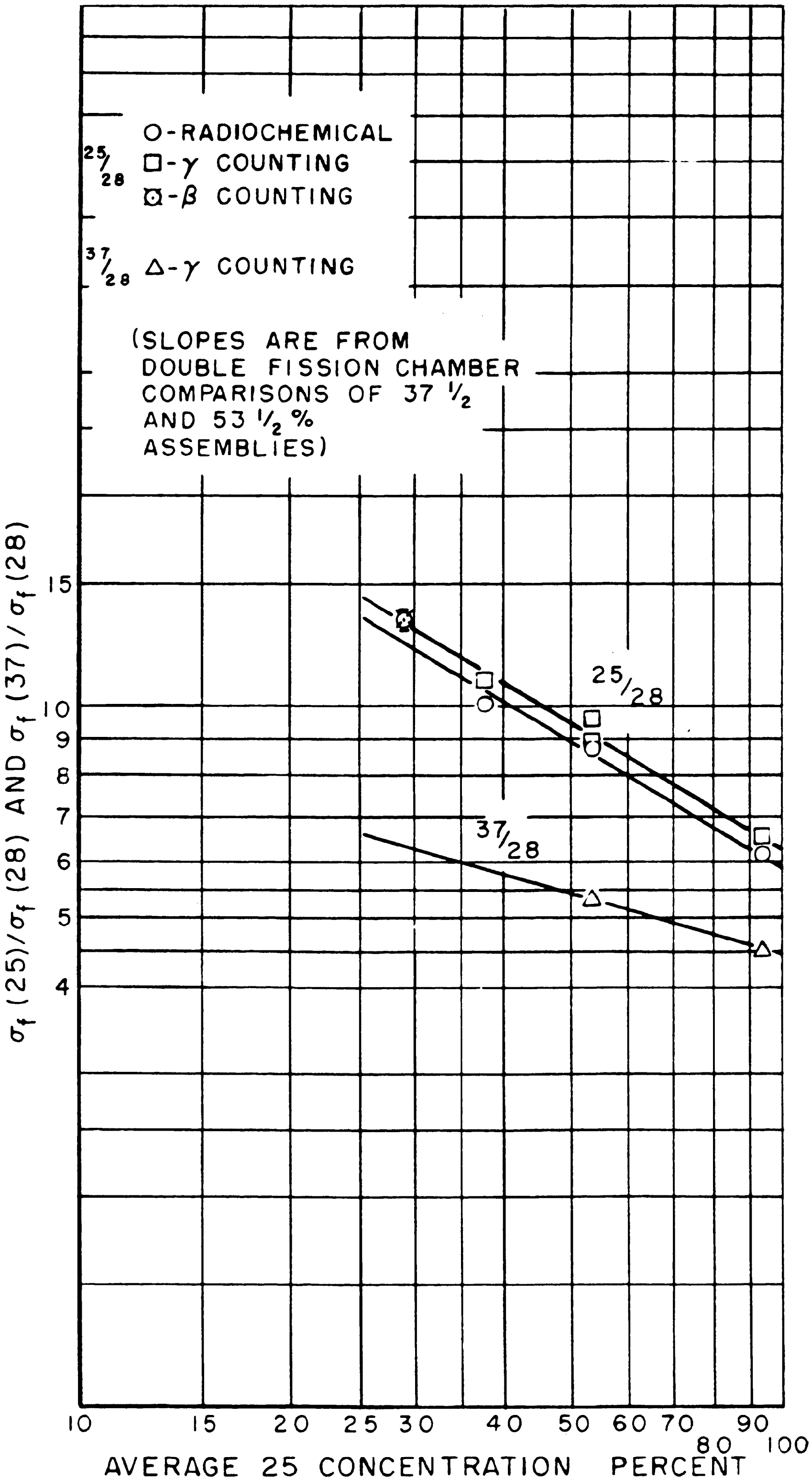

FIG. 22. The spectral indices $\sigma_f(25)/\sigma_f(28)$ and $\sigma_f(37)/\sigma_f(28)$ as functions of U-235 concentration.

critical mass and 25 concentration is essentially that reported in LA-1251[6] for oralloy with a thick reflector of normal uranium.

[6] LA-1251; Critical Masses of Oralloy at Reduced Concentrations and Density; Orndoff, Paxton, Hansen; 5/1/51.